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Tristan code and its applications

K.-I. Nishikawa

Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854-8019, USA

Abstract. Since TRISTAN: The 3-D Electromagnetic Particle Code was introduced in 1990, it has been used for many applications including the simulations of global solar wind-magnetosphere interaction. The most essential ingridients of this code have been published in the ISSS-4 book. In this abstract we describe some of issues and an application of this code for the study of global solar wind-magnetosphere interaction including a substorm study. The basic code (tristan.f) for the global simulation and a local simulation of reconnection with a Harris model (issrec2.f) are available at http:/www.physics.rutger.edu/˜kenichi. For beginners the code (isssrc2.f) with simpler boundary conditions is suitable to start to run simulations. The future of global particle simulations for a Geospace General Circulation Model (GGCM) with predictive capability (for Space Weather Program) is discussed.

1 Introduction

The interaction of the solar wind with the Earth's magnetic field gives rise to a number of important and intriguing phenomena, many of which are only partially understood. These include reconnection between the solar wind magnetic field and geomagnetic field lines at the dayside magnetopause (including patchy plasma transfer), reconnection in the magnetotail, plasma convection in the magnetosphere/ionosphere, generation of field-aligned current systems, and energetic particle injection. A wide range of physical processes is involved in the solar wind-magnetosphere system, and consequently a wide array of methods has been used to study them, ranging from detailed studies of select phenomena with the assumption of a specific field geometry or boundary conditions, to fully three-dimensional simulations with MHD assumptions.

The near-Earth magnetotail is one of the regions where kinetic effects are critical and particle simulations become essential (e.g., Birn et al., 1996; Pritchett, 2000). Based on this idea we have developed a global particle simulation model (Buneman, 1993; Buneman et al., 1992). This code has been used to study global solar wind-magnetosphere interaction with time-varying IMFs (Nishikawa, 1997, 1998a,b, 2001; Nishikawa and Ohtani, 2000a,b). Changes in the solar wind conditions drive substorms and storms. Since the variety of processes, regions, and scale lengths is involved, it is difficult to understand them. In the following sections, studies using the three-dimensional electromagnetic particle model (EMPM) have provided significant insight into the triggering processes of substorms (Nishikawa and Ohtani, 2000a,b; Nishikawa, 2001). This model makes major advances in that the electron and ion motions are separately incorporated and each species is diagnosed according to the physics involved. Through the separation of the electron and ion dynamics, a more physical picture of magnetic reconnection and substorms is attained and can be tested against observations.

The EMPM enables us to investigate the global simulation of the solar wind interaction with an IMF, in principle with the complete particle physics. As will be shown below, the advantage is that the basic equations of the model contain the complete physics. The price to be paid is that, with present supercomputers, the plasma parameters must be scaled and the resolutions in space and time are coarse. However, these weaknesses of this model will be eliminated as the power and speed of supercomputers are being increased significantly.

In this abstract we describe an introduction to global particle simulations of solar wind-magnetosphere interaction (tristan.f) (see Nishikawa et al. 2001 at ISSS-6) and reconnection simulations (isssrec2.f) (see the paper by Crew et al. 2001 at ISSS-6) whose codes can be obtained at http://www.physics.rutgers.edu/˜kenichi. These codes are 3-dimensional electromagnetic, relativistic, particle-in-cell code. For smaller memory for simulations, the code for reconnection, issrec2.f has very few grids for the third dimension (y-direction), therefore this code is quasi 3-dimensional. However, this code can be full 3-dimension by increasing the grid size in the y-direction, which will require large amount of memory. The

Correspondence to: kenichi@physics.rutgers.edu

pdf file of presentation related to the lecture note is also available. In order to understand and use these codes readers need to study in depth text books by Hockney and Eastwood (1986), Birsall and Lagdon (1991), a review paper by Dawson (1983). The basics of particle simulation are obtained by reading the chapters by Omura and Matsumoto (1993), Buneman (1993), and Pritchett (2001 at ISSS-6), the comments provided in the codes describe practical information. We believe some simulation results obtained by this code provide useful information how to use these codes. Recent development of this code using High Performance Fortran (HPF) is provided by Cai et al. (2001, at ISSS-6). This HPF Tristan code will be very useful for present and future parallel computing.

In the next section the EMPM is described very briefly. In section 3 the simulation results with southward turning IMF are briefly reviewed, including the reconnection in magnetotail. The simulation results with dawnward turning IMF after northward IMF exhibit a reconnection groove in the dawnside and duskside magnetopause, which facilitates particle entry into the inner magnetosphere (Nishikawa, 1998b) (see also the paper by Nishikawa et al. at ISSS-6). The present status and future development and perspective goals of EMPMs as a Space Weather Model are discussed.

2 Three-Dimensional Electromagnetic Particle Simulation Model (EMPM)

This code is a successor to the TRISTAN code (Buneman et al., 1980). Its new features (Buneman, 1993) are (1) Poisson's equation and Fourier transforms have been eliminated by updating the fields locally from the curl equations and depositing the particle currents according to charge-conserving formulas (Villasenor and Buneman, 1992), (2) radiative boundary conditions are applied to the fields using a first-order Lindman approximation (Lindman, 1975), (3) filtering is done locally, (4) localization makes the code ideally suited to modern parallel machines which call for minimizing data paths, (5) the code is in FORTRAN and fully transportable: modest versions run on PCs and on workstations. The new version of the code has been applied to the study of the dynamics of low-β plasma clouds (Neubert et al., 1992), the whistler waves driven by the Spacelab-2 electron beam (Nishikawa et al., 1994a; Zhao et al., 1994), and the coalescence of two current loops (Nishikawa et al., 1994b; Zhao et al., 1995, 1996).

The tristan code employs the most fundamental equations without any assumptions. These are Maxwell's equations

$$d\mathbf{B}/dt = -\nabla \times \mathbf{E} \quad (1)$$

$$d\mathbf{D}/dt = \nabla \times \mathbf{H} - \mathbf{J} \quad (2)$$

as well as Newton-Lorentz' equation

$$md\mathbf{v}/dt = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (3)$$

which includes relativistic effects.

For the simulation of solar wind-magnetosphere interactions the following boundary conditions were used for the particles (Buneman et al., 1992, 1995: Nishikawa et al., 1995; Nishikawa, 1997, 1998a,b): (1) Fresh particles representing the incoming solar wind (unmagnetized in their test run) were continuously injected across the $y-z$ plane at $x = x_{min}$ with a thermal velocity plus a bulk velocity in the $+x$-direction; (2) a thermal solar particle flux was also injected across the sides of their rectangular computation domain; (3) escaping particles were arrested in a buffer zone, redistributed there more uniformly by making the zone conducting in order to simulate their escape to infinity, and were finally written off. The EMPM used a simple model for the ionosphere in which both electrons and ions were reflected by the Earth's dipole magnetic field. Effects of a conducting ionospheric boundary will be developed in future simulations. The effects of the Earth's rotation were not included.

For the fields, boundary conditions were imposed just outside these zones (Buneman et al., 1992, 1995: Nishikawa et al., 1995; Nishikawa, 1997, 1998a,b); radiation was prevented from being reflected back inward, following Lindman's ideas (Lindman, 1975). The lowest-order Lindman approximation was found adequate: radiation at glancing angles was no problem. However, special attention was given to conditions on the edges of the computational box.

In order to avoid the problem at the edges, the subroutine edge in tristan.f and subroutines preledge and postedge in isssrec2.f are used. The idea is that at the edges the Lindman conditions need to be considered in a special way.

Initial and boundary conditions of the 3-D EM code are similar to those already used in previous works (Nishikawa, 1997, 1998a). Initially, these fill the entire box uniformly and drift with a velocity $v_{sol} = 0.5c$ in the $+x$ direction, representing the solar wind without an IMF. The electron and ion thermal velocities are $v_{et} = (T_e/m_e)^{1/2} = 0.2c$, and $v_{it} = (T_i/m_i)^{1/2} = 0.05c\,(= v_s = (T_e/m_i)^{1/2})$, respectively, while the magnetic field is initially zero. A circular current generating the dipole magnetic field is increased smoothly from 0 to a maximum value reached at time step 65 and kept constant at that value for the rest of the simulation. The center of the current loop is located at $(70.5\Delta, 47.5\Delta, 48\Delta)$ with the current in the $x-y$ plane and the axis in the z direction. The initial expansion of the magnetic field cavity is found to expel a large fraction of the initial plasma. The injected solar wind density is about 0.8 electron-ion pairs per cell, the mass ratio is $m_i/m_e = 16$, and $\omega_{pe}\Delta t = 0.84$. In the simulations reported in this paper the spacing grid Δ corresponds to approximately $1R_{\mathrm{E}}$ (The distance between the dayside magnetopause and the Earth in the simulations is about 10Δ). The time step in the simulations corresponds to about 10 seconds on the basis of the solar wind velocity, the relative distance, and the mass ratio (Due to the heavy electrons the MHD phenomena seem react fast). Time step 1152 in the simulation is set at 0.00 UT to provide a sense of relative time frame in the simulations (1088; $-$00.10 UT: 1152; 00.00 UT: 1216; 00.10 UT: 1280; 00.20 UT: 1344; 00.30 UT: 1408; 00.40 UT: 1472; 00.50

UT).

Southward turning IMF

At step 768 (-1.00 UT) (Buneman et al., 1995; Nishikawa et al,. 1995) a southward IMF ($B_z^{IMF} = -0.4$) is switched on at $x = 66\,R_{\rm E}$, and the solar wind with the southward IMF reaches about $x = 120\,\Delta(= -50\,R_{\rm E})$ at step 1280 (0.20 UT). The Alfvén velocity with this IMF is $v_A/c = 0.1(\bar{n}_i)^{-1/2} = 0.1$ for the average ion density $\bar{n}_i = 1$.

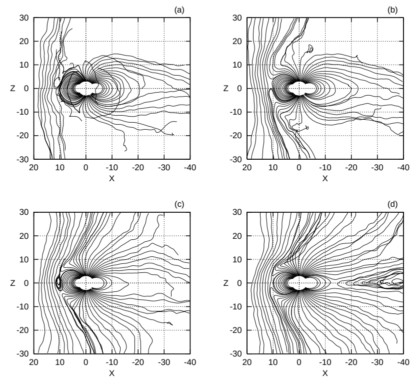

Fig. 1. Magnetic field lines in the noon-midnight meridian ($x - z$) plane containing the Earth dipole center at -0.20UT (1024) (a), -0.10UT (1088) (b), 0.10UT (1216) (c), and 0.20UT (1280) (d). The magnetic field lines are traced from near the Earth ($r = 3\Delta$ ($\approx 3R_{\rm E}$)) and subsolar line in the dayside and the magnetotail. Some magnetic field lines are moved dawnward or duskward. The tracing was terminated due to the preset number of tracing points or the minimum strength of total magnetic field.

To display magnetic reconnection at the dayside magnetopause and in the magnetotail, Figure 1 shows the magnetic field lines in the noon-midnight meridian plane at four different times. (Geocentric solar magnetospheric (GSM) coordinates are used only in Figure 1.) At -0.20 UT (1024), the solar wind with its southward IMF starts to interact with the dipole magnetic field at the dayside magnetopause (Fig. 1a). Figure 1b shows the X-point at the magnetopause at -0.10 UT (1088). The southward IMF is bent by the magnetosphere as shown in Figure 1c at 0.10 UT (1216). Figure 1c displays an interesting magnetic structure near the subsolar magnetopause. Three-dimensional analysis shows that the reconnection occurs three-dimensionally in the dayside magnetopause along the equator (see, for example, (Walker and Ogino, 1996). At the same time stretched dipole magnetic fields are observed, particularly in Figure 1c. Furthermore, the magnetic fields are stretched in the magnetotail, which leads to the growth of a tearing instability there. Figure 1d shows magnetic reconnection occurring at 0.20 UT (1280), with the X-point located near $x = 85\,\Delta$ (= $-15\,R_{\rm E}$).

As described in details (Nishikawa, 1997, 1998a,b, 2001; Nishikawa and Ohtani, 2000a,b), this model can provide qualitative insights for the substorm triggering processes. We have found the sequence of local reconnection, current disruption, dipolarization, full reconnection, bursty bulk flows (BBFs), and generation of wedge currents in the case of a southward turning IMF.

3 Discussion

The results discussed here show that even with the modest grid size of 215 by 95 by 95 cells, the three-dimensional fully kinetic model is able to generate the complete magnetosphere with some of the basic characteristics observed for southward and dawnward turning IMFs. Southward IMF causes magnetic field stretching in the near-Earth plasma sheet. The cross-field current thins and intensifies, which excites a kinetic (drift Kink) instability along the dawn-dusk direction. It should be noted that theoretical analysis (e.g., Brittnacher et al., 1994) and particle simulations (e.g., Nishikawa and Ohtani, 2000b; Pritchett, 2000) indicate that the collisionless tearing is stabilized by the electron compressibility which results from the finite normal magnetic component (B_z) in the central plasma sheet. The reduced B_z with a kinetic (drift kink) instability in the central plasma sheet apparently allows the collisionless tearing to grow (Nishikawa, 1998a; Nishikawa and Ohtani, 2000b; Pritchett, 2000). Namely, the plasma transport across tubes caused by the kinetic (drift kink) instability appears to reduce the electron compressibility effect and to allow the collisionless tearing instability to grow rapidly. Because of this collisionless tearing instability, magnetic reconnection is formed in the near-Earth magnetotail (Parnell et al. 1996; Cai et al. 2001; Büchner, 1999). At the same time, the nightside magnetic fields are dipolarized and a plasmoid is formed tailward (see, for example, Birn et al. (1996) and Walker and Ogino (1996)). A thin, intense current sheet is decreased, which is observed during substorm breakup and expansion (Lui, 2000).

This EMPM helps us to understand the fundamental physical processes that facilitate particle entry into the inner magnetosphere and ionosphere since particles are traced self-consistently. One of the unique features of this model is that solar wind particles are injected into the inner magnetosphere through the magnetopause and from the near-Earth magnetotail due to the reconnection and are accelerated self-con- sistently (Nishikawa, 1997, 1998a,b). Furthermore, the EMPM alone could include these processes well in collisionless regions from the upstream solar wind up to the upper ionosphere without the assistance of other codes. The inclusion of the ionospheric model needs to be developed with much better spatial resolutions.

As the global MHD models become an integrated part of many experimental studies, the EMPM will be also involved with these studies. In particular, Cluster II, Magnetospheric Multiscale Mission, and Magnetotail Constellation, Dynamics, Reconnection, And Configuration Observatory (DRACO) will provide an excellent opportunity for an integrated study with the EMPM and these advanced observations of macro-, meso-, and micro-scale phenomena. This synergetic study will help us to understand unsolved problems such as reconnection, substorm onset and origin of high energy particles injected into the inner magnetosphere.

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